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MINISTRY OF DEFENCE

ROYAL ARMAMENT RESEARCH AND DEVELOPMENT ESTABLISHMENT

R.A.R.D.E. MEMORANDUM 14/71

Rational performance indices for mine and minefield assessment

(title UNCLASSIFIED)

F.V. Davies, B.Sc. (E4)

Summary

Some mine assessment indices have been analytically derived. By using these it is possible to compare mines on a rational basis with lethality, cost, weight, time-to-lay and laying effort as yardsticks for assessment.

The arrangements of certain types of mixed minefields can be optimised using any one of the indices.

Some graphs are included for rapid minefield cost and field stopping power evaluation.

Approved for issue:

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LIST OF SYMBOLS

a	actuation length (semi-track width for track-cutting mine) (ft)
b	mine laying change over time (sec)
c	unit mine cost (pounds sterling)
e	probability that, given actuation and fuzing, the mine stops the tank
f	fuzing probability
l	cost of minefield per unit length of front (pounds sterling ft^{-1})
n	towing vehicle mine carrying capacity
p	row stopping power
r	number of rows
s	distance between mines in one row (ft)
w	mechanical layer laying rate (sec^{-1})
I_C	lethality/cost index
I_T	lethality/time-to-lay index
I_W	lethality/weight index
L	length of minefield front (ft)
N	number of mines covering minefield front of length L
P	field stopping power
T	overall time to lay (N/L) mines (secs)
W	weight of mines per unit length of front (lb/ft)
X	number of men involved in laying a minefield
α	probability of actuation
λ	density of mines per unit length of front for random minefield (ft^{-1})
ρ	weight of single mine (lb)

1. INTRODUCTION

The determination of effectiveness criteria for military weapon systems requires the formulation and correlation of analytical statements for the important operational parameters. It is however rarely easy in practice to define all the parameters in mathematical terms, and land mines are no exception in this respect, but five of the most important factors can be simplified and presented in analytical form. These are minefield performance (field stopping power), mine cost, time and effort to lay a standard minefield and minefield weight. Although mine assessments can be based on these criteria individually, comparisons would be of more use if the parameters could be combined in some way. It is with this problem that this Memorandum is concerned.

The most important minefield performance parameter is mine/tank lethality and this is chosen therefore as the common factor to be combined with each of the other factors. Each parameter is stated in mathematical terms, and four indices, designated lethality/cost, lethality/time-to-lay, lethality/laying effort and lethality/weight, are derived analytically.

The four indices allow assessment and comparison of mines to be made on the appropriate basis. In certain cases comparisons of minefields may also be made.

2. DERIVATION OF THE INDICES

Since the lethality parameter is common to each index, it makes a convenient starting point for the analysis. Field stopping power, (or the probability of stopping one tank attempting to cross the minefield), is a widely accepted criterion of minefield performance, and is used as the basis for the following analysis. The remaining parameters - cost, weight, time and effort to lay - are, with the possible exception of the last two, comparatively simple to define analytically.

2.1 Field stopping power for patterned minefields

The field stopping power P is given by

$$P = 1-(1-p)^r \qquad (1)\ (\text{ref } 1)$$

where r is the number of rows and p the row stopping power given by

$$p = \frac{4a\alpha ef}{s} \qquad (2)$$

where s is the spacing in feet between mines in one row, and a, α, e and f are mine/tank target functions defined in the list of symbols.

Now

$$s = \frac{rL}{N} \tag{3}$$

where L is the length of minefield front in feet and N is the total number of mines in the field.

Substituting successively for s in equation (2) and p in equation (1), then

$$\frac{4\alpha aefN}{rL} = 1-(1-P)^{1/r} \tag{4}$$

The four subsidiary parameters cost, weight, time-to-lay and laying effort can be expressed in terms of N/L and substituted into equation (4) as indicated in the following sections.

2.2 Lethality/Cost index

The cost l of mines per unit length of minefield frontage is

$$l = \frac{cN}{L} \tag{5}$$

where c is the unit cost of a mine.

Substituting for N/L in equation (4) and re-arranging so that the terms associated with the mine are grouped on one side of the equation (L H S) and those associated with the minefield on the R H S, the lethality/cost index I_c can be defined by

$$I_c = \frac{4\alpha aef}{c} = r\left\{\frac{1-(1-P)^{1/r}}{l}\right\} \tag{6}$$

The index I_c can be interpreted physically as the mine lethal actuation length obtained per unit cost. It is constant for a given mine/tank combination and can therefore be used as a performance/cost criterion. A higher value of I_c denotes a greater mine performance potential for a given cost. The index can of course be calculated from either side of equation (6), whichever is more convenient.

2.3 Lethality/Weight index

The weight W of the mines per unit length of front is given by

$$W = \rho\left\{N/L\right\} \tag{7}$$

where ρ is the weight of a single mine.

Substituting for (N/L) in equation (4) and re-arranging as before, the lethality/weight index I_W can be defined:

$$I_W = \frac{4\alpha aef}{\rho} = r\left\{\frac{1-(1-P)^{1/r}}{W}\right\} \tag{8}$$

The physical interpretation I_W is lethal actuation length per unit weight. The remarks in Section 2.2 apply with weight being substituted for cost.

2.4 Lethality/Time-to-Lay index

The time involved in laying a minefield obviously depend on factors such as the nature of the terrain and of the transporting and laying equipment as well as the type of mine being laid. In order to allow reasonably simple comparisons to be made, a standard minefield is considered for which the otherwise continuous laying process is only interrupted by stores and equipment limitations. It is assumed that the mines are laid mechanically with the aid of a mine-laying party, and that they are transported from dump to minefield by a shuttle service of three vehicles, each of which in turn acts as the mine layer towing vehicle, while the other two are re-loading or waiting to take over. If the distance between dump and minefield is not too great, the only interruption to laying occurs when the empty towing vehicle is detached from the mine layer and is replaced by a fully loaded towing vehicle. The initial period taken up by preparing the mine layer and the first towing vehicle is not included in the time to lay since this is virtually independent of mine type.

The time to lay is thus decided by three factors:

(i) the laying rate(w mines/second) of a mechanical layer which for a particular mine type is assumed constant irrespective of mine spacing

(ii) the change over time, b, from one vehicle to another

(iii) the carrying capacity, n mines per vehicle, which varies with mine type.

The time to lay may then be expressed approximately as follows:

$$\text{actual laying time} = (N/n)\,(n/w)$$

$$\text{total change-over time} = \frac{Nb}{n}$$

so that overall time to lay N/L mines,

$$T = \frac{N}{n}\left\{\frac{n}{w} + b\right\}\frac{1}{L}$$

$$= \frac{N}{L}\left\{\frac{n + wb}{wn}\right\} \tag{9}$$

Substituting for $(^N/L)$ in equation (4) and re-arranging, the lethality/time-to-lay index can be defined

$$I_T = \frac{4\alpha aefwn}{(n + w_b)} = r\left\{\frac{1-(1-P)^{1/r}}{T}\right\} \tag{10}$$

The index I_T may be interpretated physically as the lethal actuation length per time to lay one mine. The remarks in Section 2.2 apply if time-to-lay is substituted for cost.

2.5 Lethality/Laying Effort index

The laying effort B to lay $^N/L$ mines is defined in terms of man-seconds in order to give values near unity to the lethality/laying effort index I_E. Thus B=XT where X the number of men involved covers not only the purely laying operations but also essential support operations such as driving, setting out and marking.

The index I_E can be simply derived from I_T to give

$$I_E = \frac{4\alpha aefwn}{X(n+wb)} = r\left\{\frac{1-(1-P)^{1/r}}{B}\right\} \tag{11}$$

i.e.

$$I_E = I_r/X$$

2.6 'M' kill and 'K' kill field stopping power

The row stopping power p of a mine can be expressed as an 'M' kill or 'K' kill probability - there are thus two corresponding values of p for a particular mine,

$$p_M = \frac{(4a\alpha ef)_M}{s} \tag{12}$$

and

$$p_K = \frac{(4a\alpha ef)_K}{s} \tag{13}$$

from which it follows that all mines with crew killing potential will have two sets of indices, one corresponding to p_M, the other to p_K.

3. RANDOM MINEFIELDS

A minefield in which the mines are randomly distributed on the ground is defined as a random minefield.

A set of analyses corresponding to those in the previous sections can be made randomly laid minefields, with roughly the same steps.

3.1 Field stopping power

The field stopping power is given by

$$P = 1-\exp(-4a\alpha ef\lambda) \tag{14}$$

where λ is the density of the mines per unit length of front. This can be written in the inverse form.

$$4a\alpha ef\lambda = \log_e\left\{\frac{1}{1-P}\right\} \tag{15}$$

Two of the subsidiary parameters-cost and weight can be easily expressed in terms of λ and substituted into equation (15) as indicated in the following sections.

It is worth mentioning at this point that equation (15) applies if the density λ is constant or if it varies in a direction at right angles to the minefield front. If λ has a bivariate distribution and is a function of the position along the minefield front, then equation (15) and the derived indices should be applied only to elements of the minefield front.

3.2 Lethality/Cost index

The cost of the minefield per unit length of front

$$l = c\lambda \tag{16}$$

Substituting for λ in equation (15) and re-arranging to separate mine and minefield parameters, the lethality/cost index I_c can be defined by

$$I_c = \left\{\frac{4a\alpha ef}{c}\right\} = \frac{\log_e\left\{\frac{1}{1-P}\right\}}{l} \tag{17}$$

3.3 Lethality/Weight index

The weight of mines per unit length of front

$$W = \rho\lambda \tag{18}$$

Substituting for λ again and re-arranging as before the lethality/weight index I_W can be defined by

$$I_W = \left\{\frac{4a\alpha ef}{\rho}\right\} = \frac{1}{W}\log_e\left\{\frac{1}{1-P}\right\} \tag{19}$$

3.4 Lethality/Time-to-Lay index and Lethality/Laying Effort index

Random minefields can be laid in a large number of different ways: they may be dispensed from a vehicle; from a helicopter or other aircraft; or by a remote delivery system such as a rocket or mortar. In such delivery systems, the carrier, the method of dispensing, the shape, volume and weight of the mine will all have some effect on the time-to-lay. However these systems are still being assessed and it is not possible to derive realistic lethality/time-to-lay and lethality/laying effort indices on the evidence at present available.

4. APPLICATIONS OF THE MINE ASSESSMENT INDICES

Usually effectiveness comparisons of mines are made by comparing the salient features of corresponding minefields. However with the restrictions on mine spacing imposed by the mechanical layers it is seldom possible to evaluate minefields of precisely similar stopping powers, so that comparisons are not made on a like-with-like basis. The use of the indices not only avoids this difficulty and makes the comparisons more specific by correlation, but reduces the number of parameters and the time required for calculation. However it must be emphasised that the influence that the indices have on mine assessment should be a strictly limited one since they form only part of the complete framework of specification and performance.

With this warning in mind, assessment indices have been calculated for both short length and full length Opponent/Piecemeal, for the Barmine and for the Mark 7. These are tabulated below.

Table of Mine Assessment Indices for Patterned Minefields

MINE	MINE ASSESSMENT INDICES							
	Lethality/ Cost I_C		Lethality/ Time-to-Lay I_T		Lethality/ Laying Effort I_E		Lethality/ Weight I_W	
	'K' Kill	'M' Kill	'K' Kill	'M' Kill	'K' Kill	'M' Kill	'K' Kill	'M' Kill
Short Length Opponent/ Piecemeal	0.081	0.141	0.867	1.510	0.0310	0.0539	0.24	0.417
Opponent/ Piecemeal	0.084	0.139	0.947	1.57	0.0338	0.0559	0.189	0.313
Barmine	0	0.312	0	1.03	0	0.0369	0	0.266
Mark 7	0	0.175	0	0.299	0	0.00769	0	0.102

Units costs are based on figures current for the last quarter of 1970 and are as follows: short length Opponent/Piecemeal £65; full length Opponent/Piecemeal £72; Barmine £20; Mark 7 (extrapolated to 1970 costs) £18.

Time-to-lay calculations are based on the use of FV432 vehicles for carrying mines and towing LAMA Barmine layer for the Barmine and Opponent/Piecemeal mines; the Mark 7 mines are laid by the Mark 3 layer.

For the laying effort calculations the following laying party strengths have been assumed

(a) For the Mark 3 minelayer (Mark 7 mine), an actual laying party of 15 men considered plus a setting out and perimeter party of 14 with 9 drivers and an officer in charge making 39 personnel in all. (See ref.3).

(b) For the Barmine Layer, the actual laying party strength is 6 men plus a setting out and perimeter party of 12 with 9 drivers and an officer in charge making 28 personnel in all. (See ref. 4).

Referring to the table above, the higher the value of any index the better the mine performance. For example high values of I_c denote increased lethality for a given cost or a reduced cost for a given lethality.

In the table below, the indices have been referred to a common reference (short length Opponent/Piecemeal) to allow an easier comparison between mines.

<u>Comparative Index Table for Patterned Minefields</u>

MINE	MINE INDEX COMPARISONS							
	Lethality/ Cost		Lethality/ Time-to-Lay		Lethality/ Laying Effort		Lethality/ Weight	
	'K' Kill	'M' Kill	'K' Kill	'M' Kill	'K' Kill	'M' Kill	'K' Kill	'M' Kill
Short Length Opponent/ Piecemeal	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Opponent/ Piecemeal	1.040	0.990	1.092	1.038	1.092	1.038	0.790	0.750
Barmine	0	2.210	0	0.684	0	0.684	0	0.640
Mark 7	0	1.240	0	0.198	0	0.143	0	0.24

5. MINEFIELD EFFECTIVENESS

The lethality indices cannot normally be used to compare different minefield arrangements if the mine can stop a tank in a single operation; in this case the indices are independent of minefield pattern.

However where a minefield has to perform two separate functions to stop a tank (e.g. to render a plough ineffective and then to cut the track), the indices can play a useful role in assessing the minefield, through the concept of an 'equivalent mine'. In the following section this is described for both patterned and random minefields for the lethality/cost index. The weight and time-to-lay indices are not considered here, because no new point is raised, but similar procedures would allow either of these indices to be used as a basis for assessment.

5.1 The Lethality/Cost index for mixed pattern minefields

Consider a mixed patterned minefield formed from N_a mines of type 'a' arranged in r_a rows and from N_b mines of type 'b' arranged in r_b rows giving a field stopping power P against a tank fitted with ploughs.

Mines 'a' and 'b' can be replaced by an 'equivalent mine' defined as a mine type of which the same number $N = N_a + N_b$ are laid uniformly in the same number of rows $r = r_a + r_b$ to give the same stopping power P. There will be an 'equivalent mine' for each mixed minefield arrangement each with its own characteristic index. If the field stopping power P and the cost 1 are evaluated for several such minefield arrangements, then the 'equivalent mine' indices can be calculated from the R.H.S. of (6)

$$I_C = \frac{r\left[1-(1-P)^{1/r}\right]}{1} \qquad (20)$$

As an example of this technique the results from an anti-plough minefield assessment are plotted on a basis of lethality and cost in Fig. 1. The minefield consists of r_p rows of anti-plough mines (with an anti-plough capability only) set in front of r_b rows of Barmines, (with an anti-track capability only). The total number of rows, $r = r_p + r_b$. The field stopping power P and the cost 1 for a number of minefield arrangements have already been evaluated (ref. 2). From these results I_C is calculated for each arrangement from equation (20). The following points emerge from the graph.

(i) For r = const (full lines) there is an optimum value of r_b giving a maximum value to I_C. For example, for $r = 7$, $r_b = 4$ is optimum.

(ii) For a particular value of field stopping power P, (say 0.7 approx) a minefield consisting of $r = 8$ rows with $r_b = 5$ rows and $r_p = 3$ rows will have the minimum cost for mine spacing specified.

5.2 The Lethality/Cost index for mixed random minefields

Consider an anti-plough minefield consisting of two types of fictitious mines both laid randomly with densities λa and λb. Then by a

similar argumunt to that used for the mixed patterned minefields and assuming that the field stopping power P and the cost l have been calculated for several values of λa and λb, the index for each arrangement can be calculated from the R.H.S. of equation (17) i.e.

$$I_C = \frac{\log_e \left\{ \frac{1}{1-P} \right\}}{l} \tag{21}$$

A plot of field stopping power P versus the index I_C is shown in Fig. 4. This shows that for a particular value of overall density λ, there there is an optimum value of $\lambda a / \lambda$ which will make the field stopping power P a maximum.

6. USE OF THE LETHALITY/COST INDEX TO CALCULATE MINEFIELD STOPPING POWER AND COST

When the index I_C for 'M' and 'K' kills for a given mine-tank combination have been determined, the 'M' kill and 'K' kill field stopping powers and the cost per unit length of front can be quickly evaluated from Fig. 2 (if the minefield is patterned), and Fig. 3 (if the minefield is laid randomly). The curves in these graphs are derived by equating I_C with the R.H.S. of equations (6) and (17). The following sections indicate the steps in the process for the 'M' kill field stopping power P and the cost l per unit length of minefield front.

6.1 Patterned minefields

Suppose $I_C = 0.30$, c = £20 and P is required to be about 0.7. The following steps are taken:

1. Choose s = 18 feet (say)

2. Evaluate $I_C\,(^c/s) = 0.3 \times 20/18 = 0.333$

3. From Fig. 2 choose a row value r = 3 which for $I_c(^c/s) = 0.333$ gives P = 0.7

4. Evaluate $l = I_c(^c/s)^r/I_o = \frac{0.333 \times 3}{0.3} =$ £3.33 per foot of front.

6.2 Random minefields

Suppose $I_C = 0.12$ and o = £20 and P is required to be 0.7. Proceed as follows:

1. From Fig. 3 determine $I_C l = 1.22$ corresponding to P = 0.7

2. Evaluate $l = 1.22/I_C = 1.22/0.12 =$ £10 per foot of minefield front

3. Evaluate $\lambda = l/o = {}^{10}/20 = 0.5$ mines per foot.

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Part II 1955

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70/Engrs/445 1966

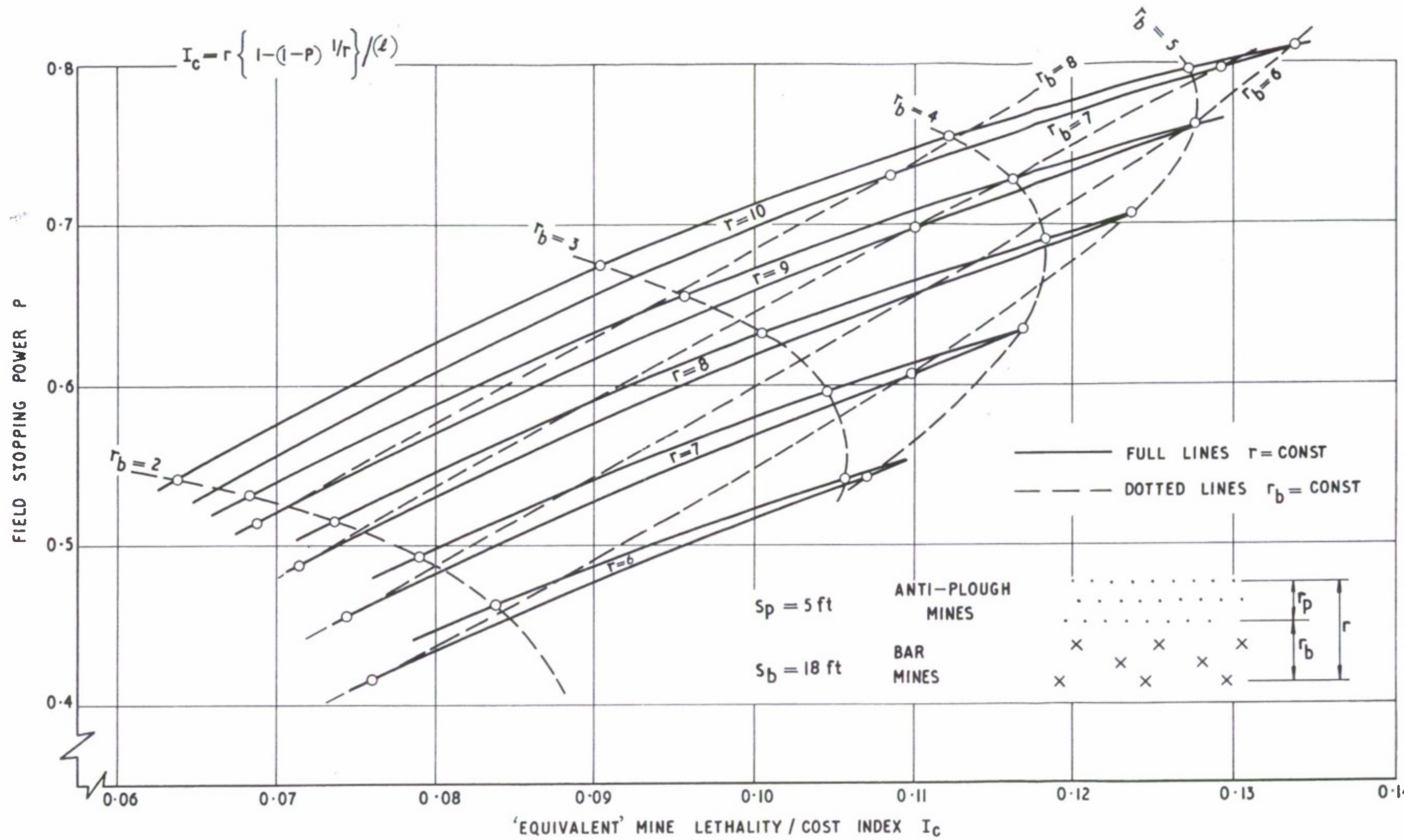

FIG. 1 ANTI-PLOUGH MINEFIELD ASSESSMENT. ANTI-PLOUGH MINES IN FRONT OF BAR MINES
FIELD STOPPING POWER VS LETHALITY/COST INDEX

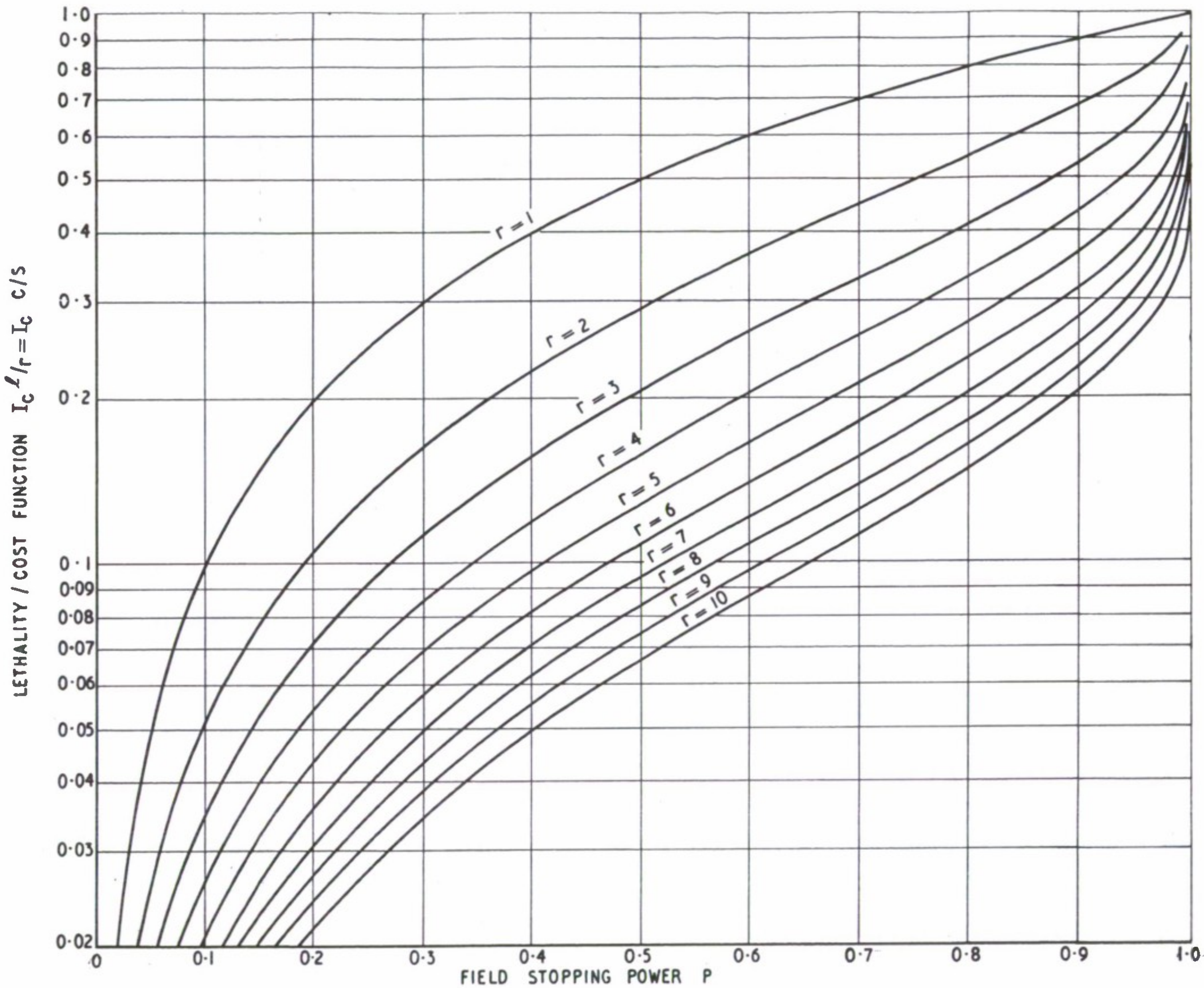

FIG. 2 LETHALITY / COST FUNCTION FOR PATTERNED MINEFIELDS

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FIG. 3

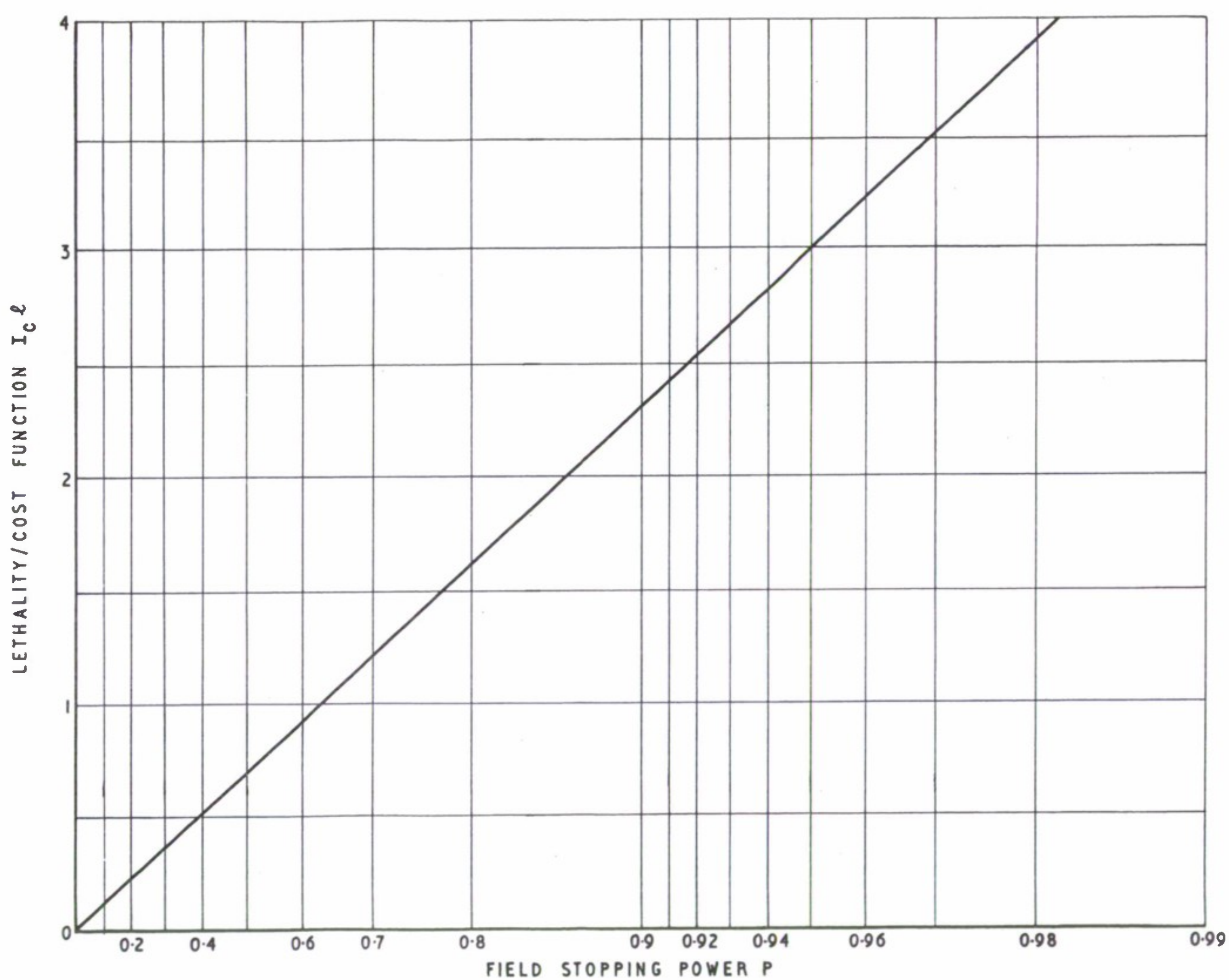

FIG. 3 LETHALITY/COST FUNCTION FOR RANDOM MINEFIEDS

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FIG.4

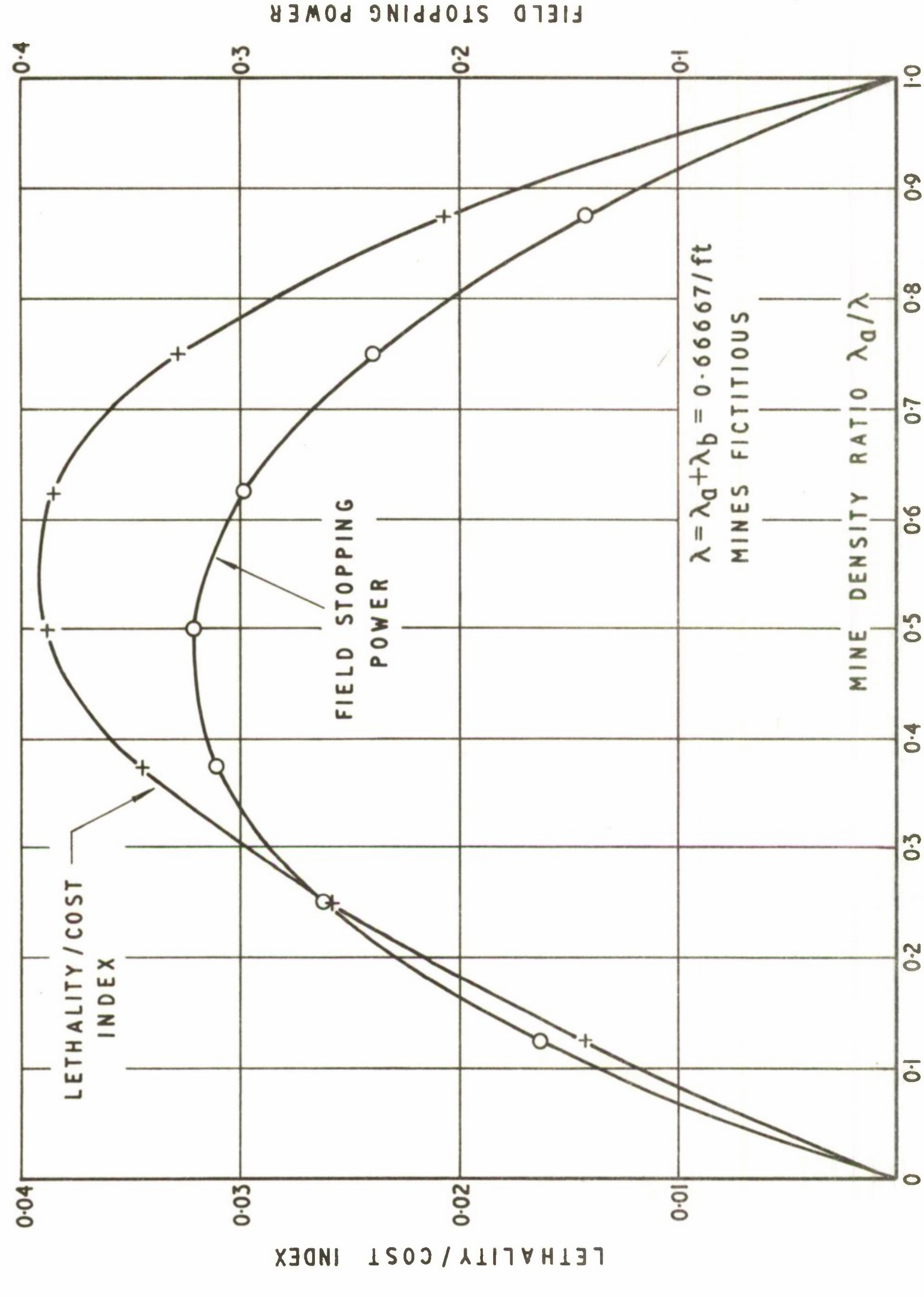

FIG.4 ANTI-PLOUGH MINEFIELD ASSESSMENT. RANDOM MINEFIELD CONSISTING OF A MIX OF MINES a AND b AT DENSITIES λ_a AND λ_b

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F. V. Davies May 1971

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Title: Rational performance indices for mine and minefield assessment
Covering dates 1971 May 01 - 1971 May 31
Availability Open Document, Open Description, Normal Closure before FOI Act: 30 years
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